

**DEEP BOREHOLE TENSOR STRAIN MONITORING,
NORTHERN CALIFORNIA**

03-HQ-GR-0088

**FINAL TECHNICAL REPORT
October 2004**

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TECHNICAL ABSTRACT

Data from five borehole tensor strain instruments situated along the San Andreas Fault in Northern California and the Hayward Fault in San Francisco Bay area have been maintained and continue to provide archive quality data for the geophysical research community, and automatically processed near-real time data for USGS internal use. Long term changes of strain rate have continued to present at San Juan Bautista since the October 1998 slow earthquake sequence. Two new episodic strain/creep events have been observed there during 2003/2004. At Parkfield, strain/creep episodes continue to be observed. A significant shift in shear strain accumulation rate at Parkfield was observed in 1998, and has continued and is correlated with co-located other instruments. Long term changes in strain rate at Chabot have been observed in 1997 and 1999, also correlated with other SF Bay instruments.

Data from the Gladwin Tensor Strainmeters has been instrumental in the ongoing proposals for a Plate Boundary Observatory, and significant effort in our project is now centred on assisting this process of establishing the planned coherent strain monitoring arrays of the future which will subsume and replace the research and development studies funded by NEHRP in this project.

OBJECTIVES

The core objective during FY2003 was a program of maintenance and analysis of deep borehole Gladwin Tensor Strain Meter (GTSM) instrumentation, initiated with two sites (Pinon Flat and San Juan Bautista) in late 1983, expanded by three sites (Eades, Donalee and Frolich) installed in the Parkfield area during December of 1986, by two sites (Chabot and Garin) deployed in the San Francisco Bay region in 1992, and Coldbrook in the San Gabriel Mountains in late 1996. (see **Figure 1**).

These instruments consist of a three component plane strain module operating at strain sensitivity of 10^{-10} and support data logging systems. As deployed they provide data sampling at 30 minute intervals for transmission via satellite for permanent archive purposes. The instruments provided by this project are unique in the

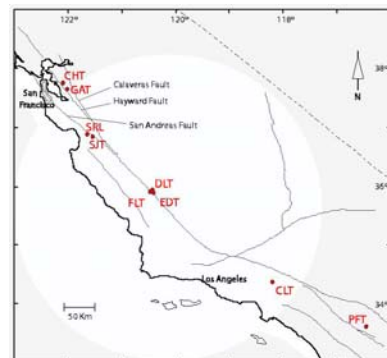


Figure 1 GTSM sites in California

program in that they have provided continuous tensor strain data for the past twenty years at a sensitivity not achievable by any other instrumentation. Data are made available in near real time in the USGS Menlo Park computer system.

The Garin site suffered irretrievable downhole damage during 1998, and has been decommissioned. In April 2002, the Eades site at Parkfield suffered irretrievable cable leakage, confirmed by field visits in May and December 2002, and December 2003.

The **immediate objectives** of the project were

- Maintenance of uphole system integrity at 5 U.S. sites in northern California, with repair or production of replacement uphole electronics if necessary.
- Manual preparation of raw instrument data for permanent archive.
- Analysis of continuous unique low frequency shear strain data (30 minute samples) and modelling studies based on the constraints of these data
- Regular reporting and real time alert response as part of the Parkfield Prediction experiment.
- Archive of processed data for access by the earthquake studies community, and provision of near-real time automatically processed data for inclusion in publicly accessible web pages linked to the USGS web datasets.
- Surveillance of other relevant observation programs and integration of associated datasets from dilatometers, creepmeters, water wells, rainfall, atmospheric pressure, laser strainmeter and 2 colour interferometer studies
- Active participation in provision of instruments and expertise for the specification and evolution of the Plate Boundary Observatory program
- Dissemination of raw and processed strain data for incorporation (via USGS personnel at Menlo Park) in the Berkeley database available in SEED format.

ACTIVITIES AND RESULTS

1) Plate Boundary Observatory.

A new activity during 1999, 2000, 2001 and 2003 has been to participate in the evolving Plate Boundary Observatory deliberations. We will provide our instrumentation and analysis capability as a core component for the PBO downhole strain work, and have been preparing for the production of larger numbers of instruments than have ever been produced. This has involved preparation of review documentation for the PBO Instrument sub-committee, production of higher quality documentation for design and fabrication, and attendance at the various focus meetings (eg. PBO workshops at Salt Lake City, Sept. 1999, and Palm Springs, Aug 2000, the Earthscope workshop at Salt Lake City, Oct. 2001, and various meetings of opportunity at AGU meetings). Though not funded by this project, these activities are a crucial project outcome because there are few qualified scientists in this area. We will continue to ensure that the technology developments of this program are available to the PBO deployment.

2) Data storage and availability.

Archived strain data from the Californian sites is stored in both raw component form, and as processed areal and shear strains. A regularly updated archive of data has been maintained in Australia with image copy in the USGS Menlo Park computer system since 1988. This data is stored in binary files with appended header information (USGS “*bottle*” format).

These data are accessible the USGS personnel in *thecove:/home/mick/BASEDATA*. Automatically processed near-realtime data is produced and available in *thecove:/home/mick/QUICKCHECK* for USGS users with access to the “*xqp*” plotting software, and automatically uploaded to the USGS crustal deformation web pages in

graphical form, managed by Stan Silverman. A fully maintained home page for download access to our source archive <http://www.cat.csiro.au/dem/msg/straincal/straincal.html> was established several years ago as a means to deliver quality archive support to the wider community. The raw instrument data are also forwarded to the raw data storage system which was established in 2000 on the U.C. Berkeley archive.

Scientists requiring further access to the archived data, other associated information or wishing to involve in collaborative effort in this area should contact Dr. M.T. Gladwin (+61 416 066 893 or by email mike@gtsmtechnologies.com).

3) Long Term data collection-all California sites.

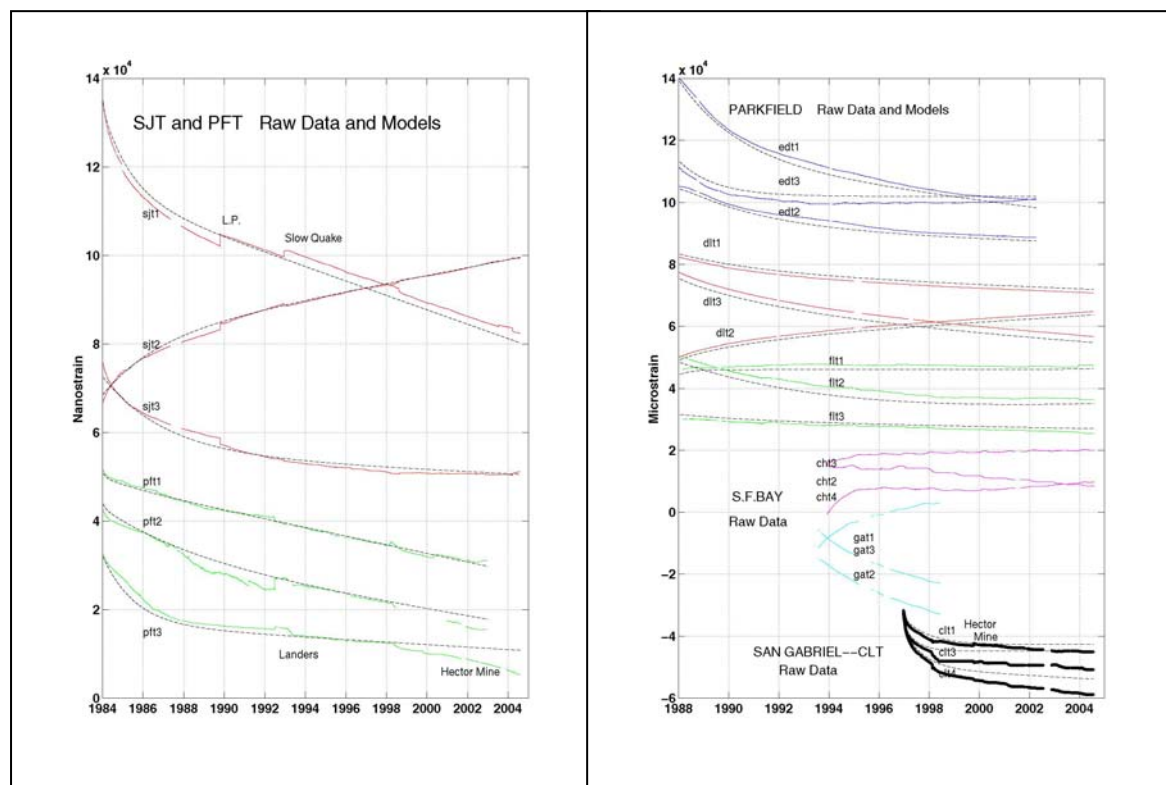


Figure 2(a) Long term raw gauge data from the two instruments installed in 1983, San Juan Bautista (sjt1, 2 and 3) and Pinon Flat (pft1, 2 and 3). Dotted curves indicate fitted exponentials removed from these data to correct for the long term strain readjustment of the borehole inclusion. These exponentials are not relevant to regional and tectonic strain measurements. Major offsets in data correspond to the Loma Prieta earthquake, the December 1992 slow earthquakes for SJT, and the Landers earthquake for PFT.

(b) Long term plots for the Parkfield sites (edt1,..., flt1,..., & dlt) installed in 1986, and the Hayward fault sites installed in 1992 (cht and gat). Donalee (dlt) gauges have a higher gain, and are plotted with a larger scale to allow presentation of all site data at the same scale. Long term inclusion adjustment models are shown also for the Parkfield data. In each case data is plotted from some months following deployment, when grout cure effects, but not borehole recovery effects, are minimal.

Long term performance of each instrument is shown in **Figure 2**, plotted in each case from some months after installation. Three raw gauge signals are shown for each site. Data from borehole inclusions are initially dominated by grout compression of the instrument, by thermally controlled decay as the instrument site re-establishes equilibrium with its surroundings and by an exponential recovery of the virgin stress field relieved at the borehole during the drilling process. The exponential signals have no relevance to the monitoring of regional strain changes and are

identified by least squares fitting for each component using the first four years of data. They are then removed from all subsequent data prior to interpretation.

During FY 2002-3, component data for all sites has been reviewed for the current relevance of the models previously used all of which were produced using data for the first four years of operation. For DLT, and SJT, models are now calculated over longer periods than used before, and the new residual data are used to calculate strain. All archived data in Menlo and on our download website reflects these changes. A table of the fitting equations for all components is available on line http://www.cat.csiro.au/dem/msg/straincal/oct2004models_str_tab.pdf.

4) Parkfield

The Eades site failed catastrophically in 2002 after 16 years of operation. During installation, as also occurred at the Garin site, the cable winch pulley failed and damage was sustained to the outer two layers of the cable waterproofing. This damage was field repaired at the time, and it is assumed that this repair was inadequate. The cable has been extensively diagnosed, and recovery is not possible. Replacement of this site should be a high priority in PBO.

Further analysis of the strain field observations at Parkfield has continued. Relevant Sacks-Evertson sites have been processed to eliminate the borehole recovery effects, and the results compared with the GTSM data sets.

Due to differing sign conventions, it is necessary in the comparison to invert the sign of the dilatometer data. The DLT site at which both instruments are co-located is particularly interesting. Both instruments show strong pore pressure response at the annual level, the dilatometer directly, and the GTSM dominantly in the areal component. The dilatometer shows long term changes of strain rate in 1993 and in 2000 both of which also show in the GTSM shear terms but not strongly in the areal strain. The delay between the clear rate change at the Eades site beginning in late 1997, and onset of this change at the Donalee site is clear on both Donnalee instruments. Over the fourteen years shown, both instruments exhibit total fluctuations in residuals of less than two microstrain indicating high stability of both systems. The strain rates established following the 1997 event are persistent to the present day.

This comparative study is continuing, and comparison with the EDM data over this area which confirmed the 1993 event, is also ongoing.

The San Simeon earthquake of December 22, 2003 provided the largest signal seen for several years at the Parkfield sites. This prompted a review of the calibration of both these sites. Completion of this has confirmed the seismic offsets for the San Simeon M6.5. The FLT site showed a very large areal response to the event probably indicating a localised fluid effect of some kind.

Site	areal	Gamma 1	Gamma 2
DLT	65ne	25ne	351ne
FLT	2.45Ue	-26ne	610ne

The Okada modelled solution for DLT gave areal= 54ne, gam1= 34ne, and gam2= 356ne, for strike=11;ss=.45;dip=49;length=24;width=15;ds=1.36. The solution for DLT is reasonably good

as can be seen in the table alongside.

For FLT, the areal **measured** result is unreasonably large, and the solution (strike=11;ss=-.59;dip=49;length=24;width=18;ds=1.4;) which satisfies DLT is close to that which satisfies

both FLT shears but not the areal.(FLT Okada modelled solution for areal=24, gam1= -31, gam2= 533.)
It is likely that the FLT areal response is localised in the immediate vicinity of the borehole.

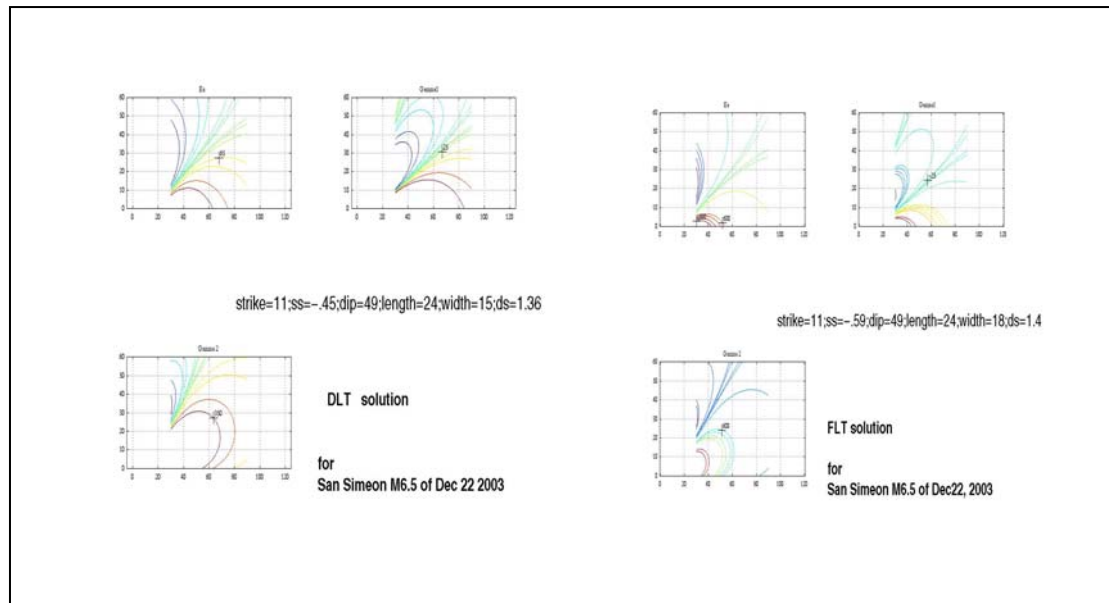


Figure 3a: Modelled solutions for DLT

Figure 3b: Modelled solutions for best fit of San Simeon at FLT

The data are plotted from just before the San Simeon to Jan 31st, 2004.

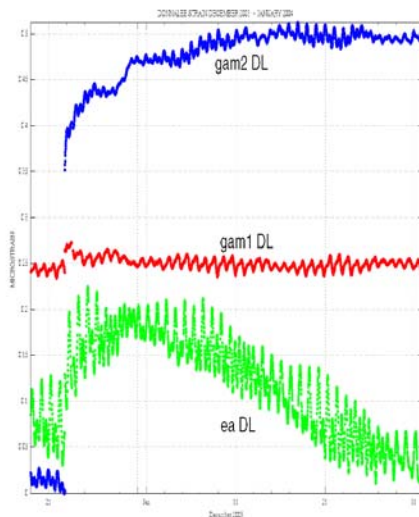


Figure 4a: San Simeon at DLT

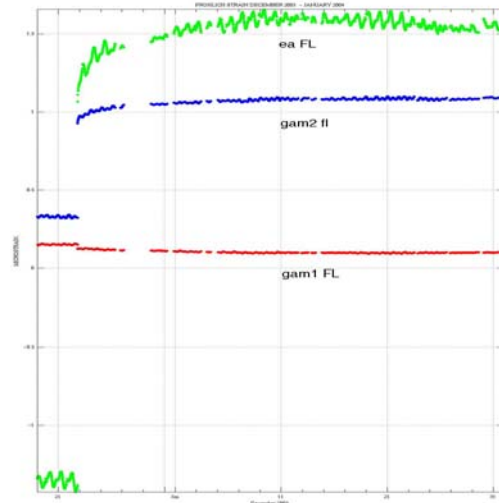


Figure 4b: San Simeon at FLT

Since May 2003, FLT channel 2 data has required considerable editing to eliminate noise particularly in the hotter months of the year. The temperatures in the site cabinet at FLT regularly run at between 45 and 62 degC during the summer. No noise effects have been present anywhere near the San Simeon earthquake timing, and this increased noise is unlikely to be adversely affecting the resultant measurement for the coseismic offset for this event.

5) San Juan Bautista

The long term data for San Juan Bautista are shown in **Figure 5**. These data indicate that with the exception of the known six events at this site (Loma Prieta, and five slow quakes (1992, 1996, 1998, 2003, and 2004) the strain rate between events is remarkably constant. This piecewise linear behaviour around a near constant strain rate is now under study, and appears consistent with observations of the total strain release of the area over a series of contiguous events previously reported (Gwyther et al., 2001, 2000). Over the 21 year record, the strain rate has been constant to \pm a few microstrain.

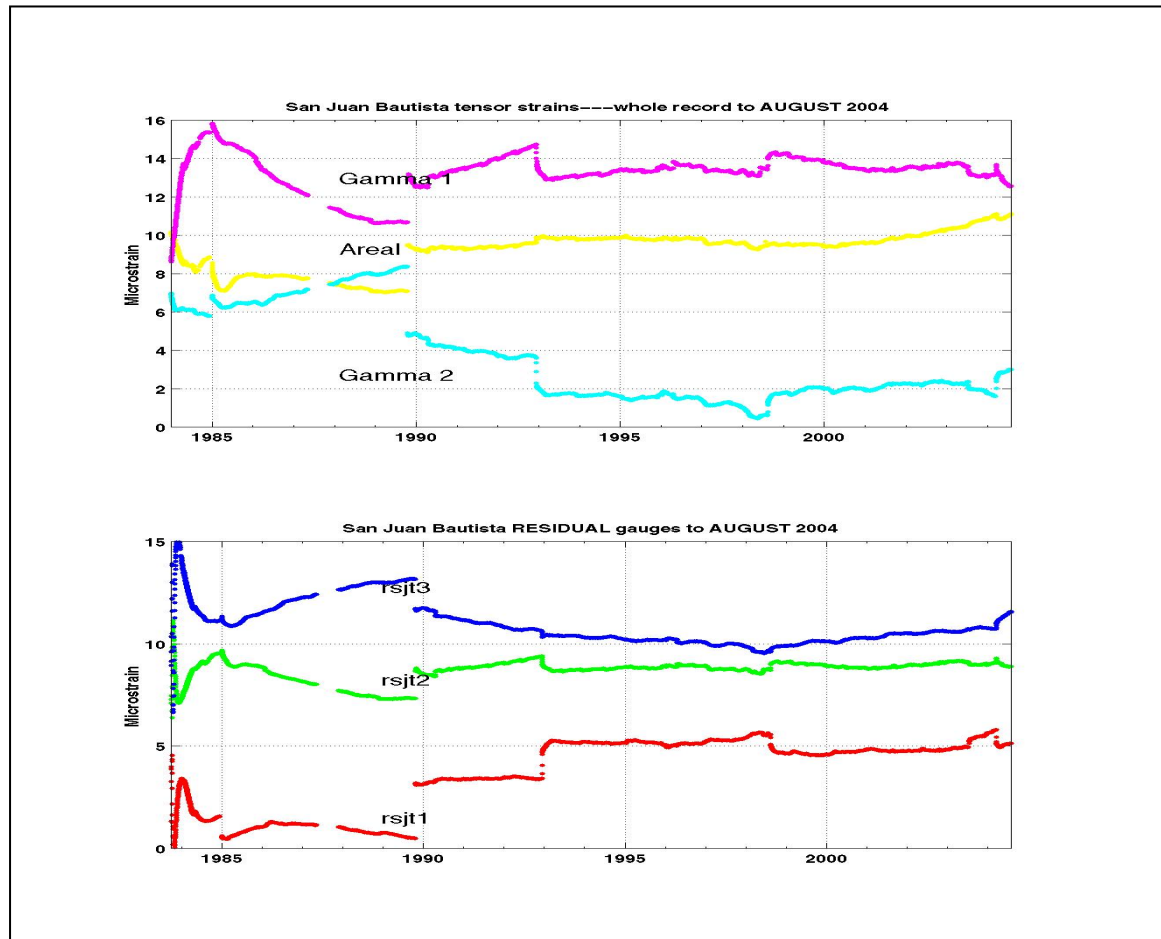


Figure 5 Long Term record of GTSM strain residual data at SJT in top panel ,
and component residuals in bottom frame.

We continue to observe co-seismic offsets associated with earthquakes in the vicinity of the strainmeter sites. **Figure 6a** illustrates a recent offset from the San Simeon earthquake M6.5 of December 22, 2003. The strain offsets in this event were -11 ne (Gamma 1) and -26 ne (Gamma2), with no change in areal.

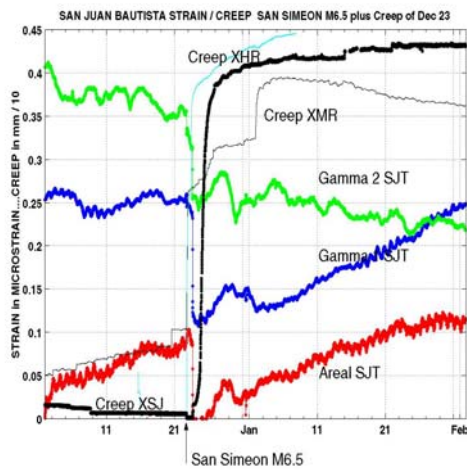


Figure 6a: Strain & Creep at SJT for San Simeon with M6.5, December 22, 2003

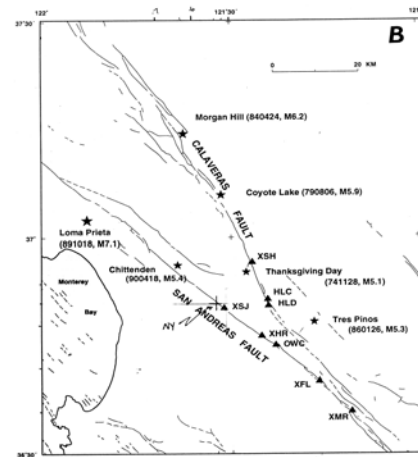


Figure 6d: shows creepmeter locations reference to SJT

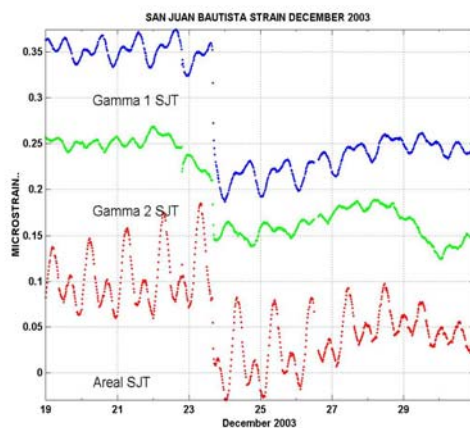
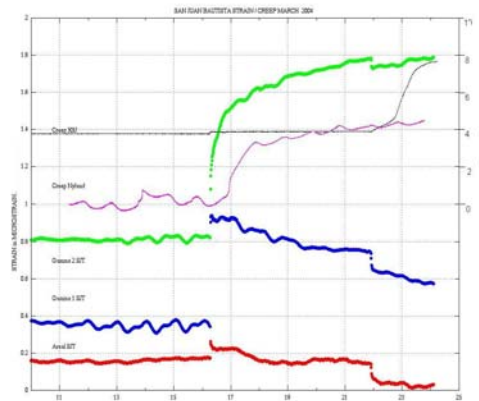


Figure 6b: gives detail of coseismic offset of San Simeon M6.5 and **Figure 6c:** the strain/creep event of the next day (Dec 23, 2003) seen at 3 creepmeters in the San Juan Bautista area



The rate of incidence of strain/creep events at San Juan Bautista is unchanged at two/year. An example of a recent event, **not** characteristic of the previously published strain/creep events, is shown in **figure 7a**. This event was initiated by a M4.3 eq. near the SJT site, and resulted in a slow quake of similar magnitude. An M3 initiated the slow quake (~M4.9) of July 13, 2003. A more characteristic episodic strain creep, similar to those seen at this site over the past 21 years is shown in **figure 7b**.

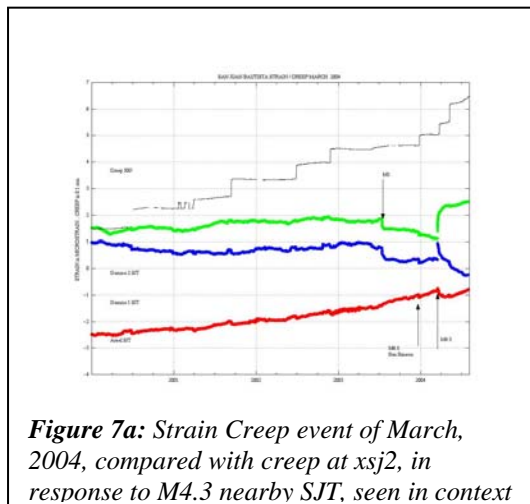


Figure 7a: Strain Creep event of March, 2004, compared with creep at xsj2, in response to M4.3 nearby SJT, seen in context

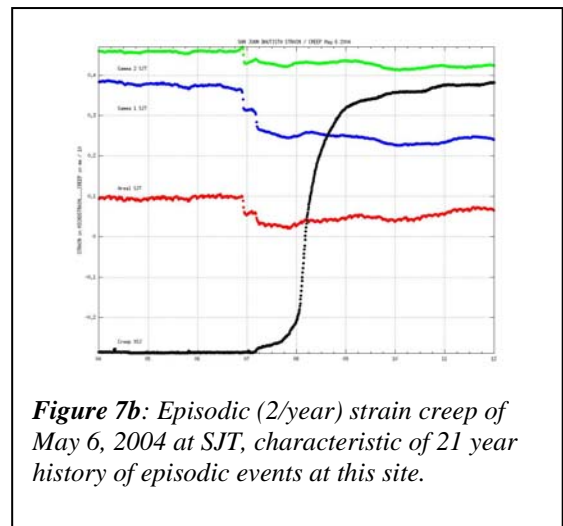


Figure 7b: Episodic (2/year) strain creep of May 6, 2004 at SJT, characteristic of 21 year history of episodic events at this site.

Comparison of Slow quakes of Aug 98 and July 2003 were reported in the Annual Technical Summary to this award in April 2004. The relatively diminished creep at xsj2 preceding both the July 2003 slow quake and the San Simeon M6.5 of December 2003 has now resumed original trends with the March 2004 slow quake.

Plot of March 2004 slow quake is included for relevance, **Figure 7c**.

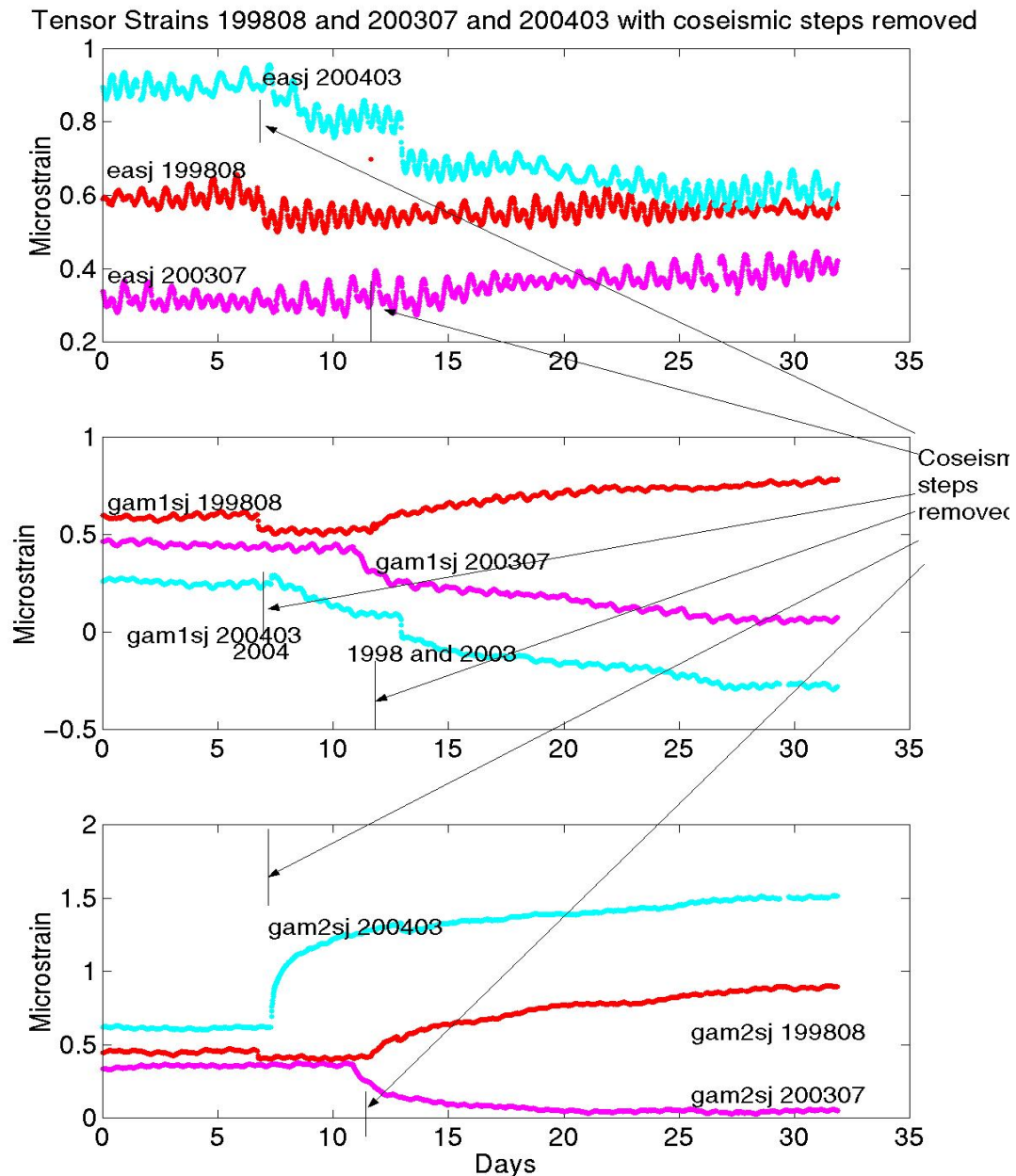


Figure 7c: Comparison of slow earthquakes of 9808, 0307, and 0403 at SJT

Red traces refer to **1998** event and **magenta** traces refer to **2003**, and **cyan** traces to **2004**. All coseismic steps have been removed, vertical bars represent timing of the removed steps. 1998 slowquake is estimated to be M4.5. Events are all of similar magnitude and duration and show dominantly in the shear data.

It seems worthy of notice that all the events of 2004 (San Simeon at PKF and SJT, slow quake 2004-03 SJT) have significant gamma2 response.

6) San Francisco Bay- Chabot

The strain rate anomaly beginning in late 1999 which was previously reported is continuing. Investigation of the dilatometer residuals data from the GA01 and RR sites indicates that this anomaly was also present in both these sites, and that it continues to the present in these sites also.

Chabot site (CHT) shows large seasonal strains associated with the water levels/storage volume in the nearby Upper San Leandro Reservoir. The correlation is shown in **Figure 8**, where the direct reservoir effect is dominantly on the areal strain with minimal perturbation on the shears. These effects are exacerbated by the strong topography between the reserve and the site.

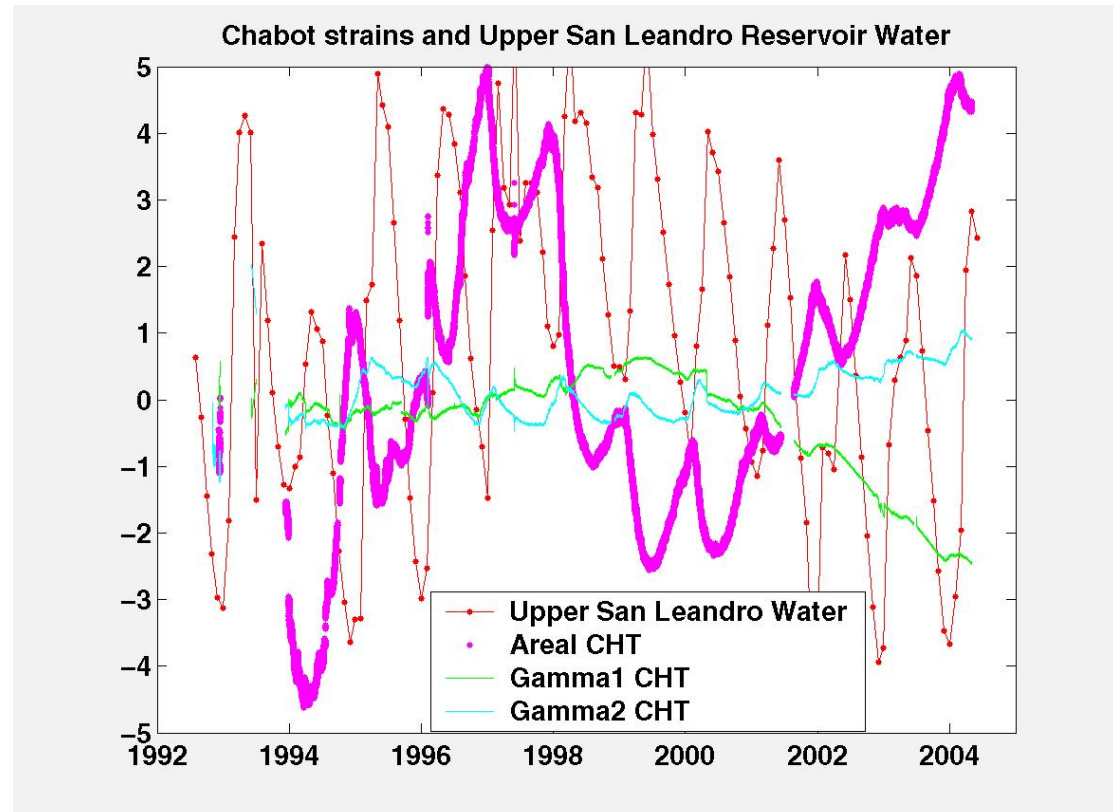


Figure 8 Long term plots of strain data at Chabot with Upper San Leandro Reservoir water levels.

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